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Utilization of the EBIS with RFQ Linacs*

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Summary

The radio-frequency quadrupole (RFQ) is a new linear accelerator structure in which rf electric fields are used to simultaneously focus, bunch, and accelerate an ion beam. Since the RFQ can provide strong focusing and adiabatic bunching at low velocities, it can capture almost all of the ions extracted from an Electron Beam Ion Source (EBIS) at a low voltage and accelerate them to an energy of 1-2 MeV/nucleon in a distance of only a few meters. A successful test at the Los Alamos National Laboratory has confirmed the calculated performance of this structure and has stimulated interest in its use with the EBIS for a variety of applications. The general properties of the RFQ are reviewed, and the utilization of the EBIS with this structure is discussed. Several design examples of this combination are also presented.

Introduction

Soon after work began at the Los Alamos National Laboratory on the study of the radio-frequency quadrupole accelerator as a low-velocity linear accelerator, interest was created in the use of the EBIS with this structure. Computational studies of this combination began in 1979 and a preliminary design resulted from these studies.[1] These design studies have continued through the successful testing of a proton RFQ at Los Alamos, and the designs for RFQ linacs to use with the EBIS have improved with the continued improvement in the ability of the theorists to realistically design them and predict their performance. This design work has resulted in a proposal to construct an EBIS at Los Alamos for continued development of this combination.

The adaptation of the EBIS to various particle accelerators was discussed at the previous EBIS Workshop[2] and this is an attempt to update that discussion by showing the advantages that the EBIS RFQ combination can produce in most accelerator applications. Several design cases for different accelerator

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applications will be presented to emphasize this point and to clearly delineate the advantages of this combination. The adaptation of this combination to synchrotrons, synchrocyclotrons, cyclotrons (axial or radial injection), and to linear accelerators has been considered.

EBIS

The EBIS, introduced in 1967 by Donets at Dubna,[3] is now being developed in many laboratories around the world, as seen from these Proceedings. These programs have used or hope to use the highly-charged ions from the EBIS for injection into synchrotrons,[4,5] cyclotrons,[6] or linacs.[7] The EBIS is also being used for atomic physics experiments[8,9] and for fusion-energy related measurements.[10] There are many variations of this ion source that have been recently reviewed[11] and presented at this workshop. The purpose of this paper is not to discuss any new development in the technology of this ion source, or to judge which approach is the best, but to discuss the optimum utilization of the highly-charged ions for all but low energy atomic physics applications.

The EBIS clearly has an advantage over conventional ion sources and over the ECR in the charge states of heavy ions that are obtainable. The very low emittance ion beam extracted from the EBIS is also an advantage for transporting and injecting the ions into an accelerator. However, the inverse ratio of the maximum charge state to the duty factor of the ion source is a disadvantage in all accelerator applications but that of the synchrotron.

Since the charge per pulse is a constant for the EBIS in all applications (with a practical limit of 10^{12} charges/pulse[11]), the first improvement that is needed in present accelerator applications is to get all of the ions from each pulse into the accelerator. In the calculations presented here to show how the RFQ can do this, the results are given for each pulse as if it were a dc ion beam, so the results are independent of the duty factor.

RFQ Linear Accelerator

The RFQ accelerating structure, first proposed by Kapchinskii and Teplyakov of the USSR in 1970,[12] is currently being developed at the Los Alamos National Laboratory as an improved low velocity linear accelerator. This program began in 1978 and an experimental model of this structure was tested very successfully in a series of measurements in 1980.[13] These tests confirmed the usefulness of this structure as a low-velocity accelerator, and verified the beam dynamics and resonator design calculations. The success of this effort has generated great interest in the use of the RFQ, and various applications of the RFQ as a low velocity accelerator have recently been reviewed.[14,15] In this paper the general characteristics of the RFQ will be briefly summarized and the designs that are of interest for EBIS utilization will be detailed.

The RFQ uses rf transverse electric fields to focus ions traveling along its axial region. Figure 1 is a schematic section of the RFQ resonator. It operates in a modified TE_{210} mode in which the currents flow transversely to the z-axis. At any given time the voltages on adjacent pole tips are the same value but opposite in sign, producing a quadrupole focusing, or defocusing force in a given transverse plane. One-half cycle later these forces reverse sign to produce an overall strong focusing effect. The focusing force at any given time is spatially continuous along the z-axis. If the pole tips have a constant radius, only a radial focusing force is present. In Fig. 1, the pole tips have a sinusoidal-like variation in radius. Between the x-plane and y-plane this variation in radius of the pole tips is shifted by $\beta\lambda/2$, where $\beta = v/c$ and λ is the wavelength of the rf excitation. This pole-tip modulation produces longitudinal accelerating fields, in addition to the transverse focusing field.

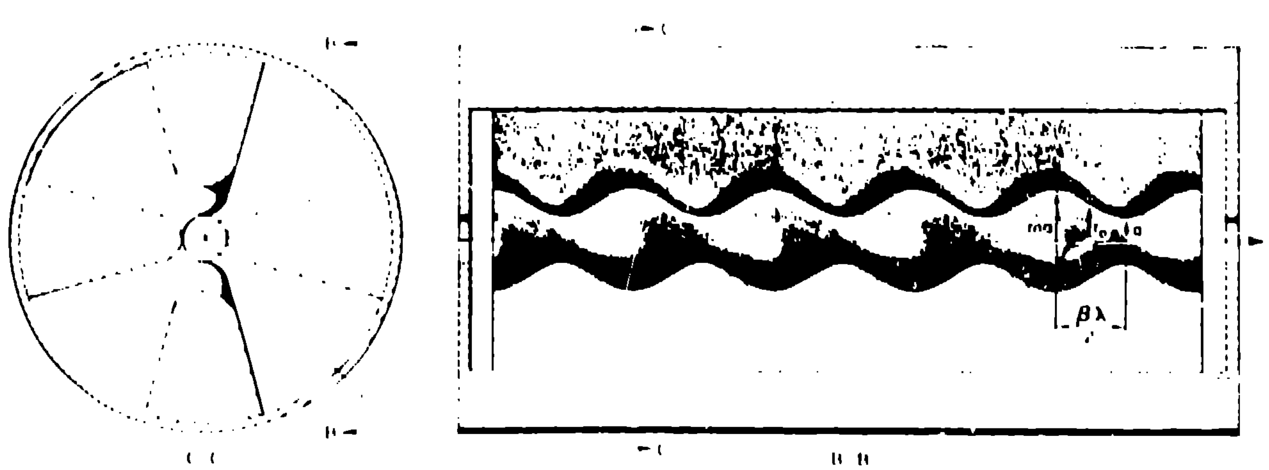

Fig. 1. Schematic Drawing of an RFQ Resonator.

Since the radial focusing is obtained from the velocity-independent electric force, the RFQ can operate at velocities below that of conventional magnetically focused linacs. This permits adiabatic bunching of the dc input beam within the linac by a gradual introduction of the longitudinal electric fields, resulting in high capture and transmission efficiencies (> 90%), even at high currents. Adiabatic bunching is not restricted to low energy in principle, but its application at high energies is prohibitive because of the length required. Since the bunching and accelerating functions are combined in the RFQ such that the adiabatic bunching occurs while the beam is being accelerated, the space-charge limit of this structure is significantly greater than for a conventional linac in which the beam is bunched before injection into the accelerator. However, the high beam capture obtained with the RFQ can make the most effective use of ions obtained from any ion source, since the space-charge limit of the structure can be lowered for low current applications thus making the structure shorter and more efficient.

In comparing the RFQ with a dc accelerator at the same output energy, the RFQ frequently offers the advantage of a much reduced size and it offers greater flexibility in the use of ion sources since a physically large and complex ion source such as the EBIS can easily be used as an injector. For convenience in operation of the ion source, a dc bias voltage can be applied to the RFQ resonator so that the ion source is at ground potential. Also, since the rf amplitude is the only physical parameter to be adjusted, the RFQ is relatively simple to operate as compared to most other accelerators. The only disadvantages of the RFQ are that the output energy variation is less flexible than dc accelerators and its efficiency is less than conventional linacs above about 2 MeV/nucleon. However, its duty factor can be adjusted from a very low value to CW operation with the same performance parameters as long as adequate cooling and rf power are provided. Therefore, the RFQ can be operated at the duty factor of the ion source, increasing the efficiency of the system.

Thus, an RFQ can be designed to accept an intense unbunched ion beam from a low-voltage dc injector and provide radial focusing and bunching with acceleration to about 1-2 MeV/nucleon in a few meters. In applying the RFQ to a specific case, it is possible to optimize its characteristics in a flexible way to obtain the desired compromise between transmission efficiency, emittance growth, beam current capacity, overall length and power dissipation.

The resonator and manifold geometry to provide rf power to the RFQ and the beam dynamics and pole-tip design procedures for the RFQ have been previously described.[16,17,18] The results of the full-scale experimental test conducted at Los Alamos in 1980 have also been presented.[19] It should be pointed out that these experimental results were in excellent agreement with the theoretical calculations performed on this structure, particularly near the design current for the system. In addition, the performance and reliability of this system during many months of measurements gave credibility to the use of this structure in the wide variety of applications that have been planned or have been discussed.[20]

The EBIS-RFQ Combination

The great flexibility inherent in the RFQ concept suggests its use in a wide variety of EBIS applications. Recently, we have made preliminary RFQ beam dynamics designs for a large number of accelerator systems with a wide variety of requirements. These included several designs for EBIS utilization and one that could be used with an EBIS as well as other ion sources. The four systems chosen to illustrate the strength of this combination are presented in Table I. The current used for each calculation was 0.5 mA electrical current, or 10^{11} charges extracted in a 30 μs pulse. The performance in each case would be the same or better for longer pulses and is independent of the duty factor. The normalized emittance used for each calculation is 0.12π mm-mrad, the experimental value reported for CRYEBIS.[21] The quantity E_s is the assumed maximum surface electrical field on the RFQ vanes and the quantity V is the rf voltage on the vanes. The quantity ϕ_s is the final synchronous phase of the bunched beam and r_o is the average radius of the vane tips from the beam axis. The peak rf power per meter of each structure is given as $\hat{P}_{rf}$ and the normalized emittance growth in each structure is given by E_o/E_i. The length L is the total length of the RFQ vanes; the resonator tank would be slightly longer for mounting and tuning the RFQ. The diameter of the RFQ resonant cavity is inversely proportional to frequency and is about 32 cm at 200 MHz.

The RFQ linacs presented in Table I are design examples, not final construction designs. The high current design codes were used with very simple assumptions for the transverse current limit and RFQ acceptance to generate these low current structures. Thus, these examples are not optimized designs,

Table I

RFQ Linacs for Use With an EBIS

	Medical Linac	Synchrotron Injector	Linac Injector	Nuclear Physics
q/A	0.5	0.4	0.5	0.25 to 0.5
f (MHz)	440	440	200	200
W_i (keV/nucleon)	10	20	10	12.5
W_f (MeV/nucleon)	1.5	2.0	1.0	1.0
ϕ_s (deg)	-30	-30	-30	-26 to -63
E_s (MV/m)	40.6	40.6	25.7	28.7
V (kV)	56	57	61	78
r_o (cm)	0.19	0.19	0.32	0.37
L (m)	3.3	6.3	2.3	4.25
$\hat{P}_{rf}$ (kW/m)	85	88	32	52
Transmission (%)	100	99	98	96 to 99
E_o/E_i (normalized)	1.05	1.12	1.13	1.26
L_1 (m)*	2.15	3.15	2.3	4.25

*For comparison in these examples, the RFQ length of each with a final energy of 1 MeV/nucleon is listed as L_1.

but can serve as starting points in consideration of these systems. The performance and efficiency of each one would improve in a final optimized design.

The first example in Table I is the RFQ that has been designed for utilization of the EBIS with the PIGMI technology. This combination of technologies would provide the optimum low duty-factor heavy ion linac for the acceleration of all fully stripped ions up to calcium (q/A = 0.5) for use in medical therapy.[2] In this accelerator the maximum charge state (fully stripped) is attained by the use of the EBIS; the maximum transmission through the linac (∿ unity) is attained by the use of the RFQ; and the maximum accelerating gradient and efficiency are attained in the high energy structures (within the rf sparking limits) by the use of high frequencies and a low duty factor. In addition, the low duty factor required for the accelerator is a perfect match to the duty factor required in present EBIS's for the production of these ions. This low duty factor, combined with the high energy gain used in this system minimizes the accelerator length, cost, and power consumption. The results of a beam dynamics calculation with PARMTEQ for the ions injected into the RFQ of this system at 10 keV/nucleon are shown in Fig. 2. On the left side, the beam characteristics are plotted versus cell number. The top plot shows the bunching of 360 particles initially distributed uniformly in phase (unbunched). The ordinate is the particle phase minus the synchronous phase. The bottom plots shows the particle energy minus the synchronous energy. In these plots, the dotted lines give the location of the zero space charge separatrix. On the right side, the x-y distribution, and the energy and phase spectra are plotted for the particles of the end of the last cell.

The second example is the extension of the first case to ions with a charge-to-mass ratio as low as 0.4. This RFQ could be used with an EBIS to inject ions much heavier than calcium (as high as xenon) into a high gradient drift tube linac. At 10-20 MeV/nucleon this system could provide ions for low-energy heavy ion physics or for injection into a synchrotron or separated sector cyclotron. Since this combination will capture all the desired ions from an EBIS, and accelerate them to the optimum synchrotron injection energy, the synchrotron output is greatly improved over that using conventional injection with an EBIS. In the case of injection into a separated sector cyclotron, or radial injection into a solid pole cyclotron, the mismatch in

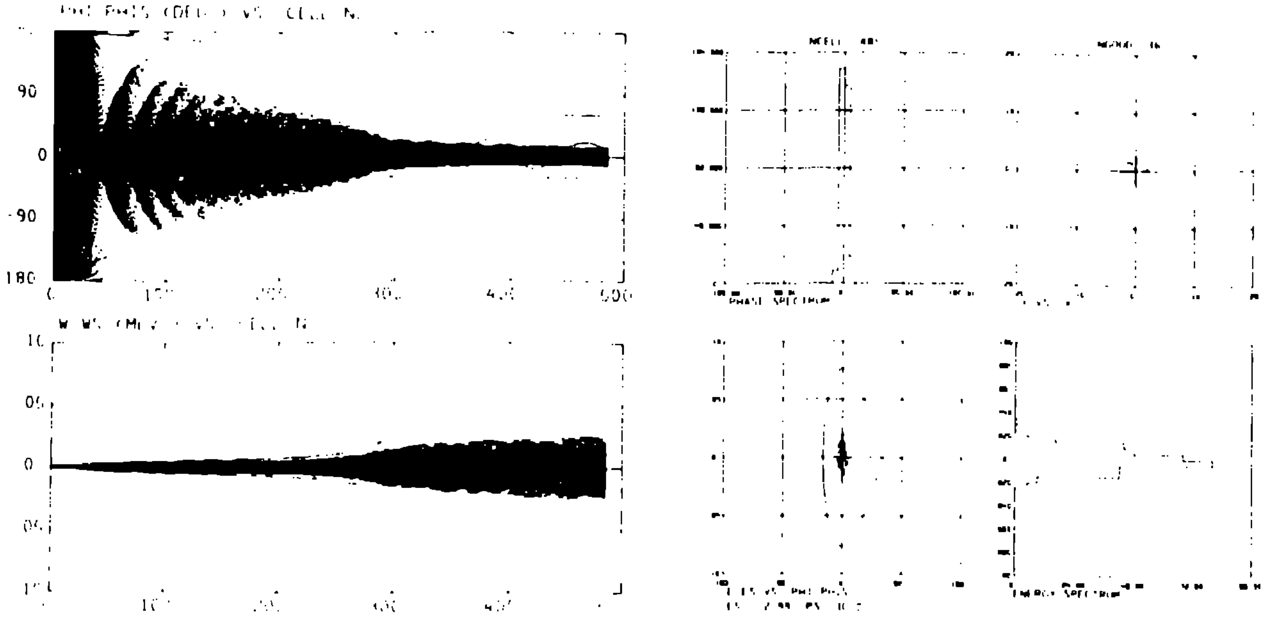

Fig. 2. The calculated beam dynamics for q/A = 0.5 ions in a 440 MHz RFQ.

frequency is so large that the cyclotron could be injected with a beam that is essentially dc from the RFQ-EBIS combination by the use of a drift distance after the RFQ to allow debunching of the beam.

Since many high- or medium-energy accelerator facilities have a 200-MHz drift-tube linac, the third example is a repeat of the first one, but at a frequency of 200 MHz instead of 440 MHz. This combination of EBIS and RFQ could then be used with an existing 200 MHz deuteron linac for acceleration of ions up to calcium for nuclear physics use or for synchrotron injection.

In the last example, the beam dynamics are given for EBIS utilization of an RFQ designed as a high-current nuclear physics facility.[15] This example was for a low-energy accelerator with two modes of operation; one for q/A = 0.25 beams, and the other for q/A = 0.5, with ion currents ranging from 10 to 25 mA. The RFQ design is determined by the requirements for q/A = 0.25 acceleration, but the same accelerator then provides even better performance for all larger values of q/A, up to the q/A = 0.5 ions. The same improvement is true for lower currents. At the design currents for this accelerator, the capture efficiency is 85-90%, but at EBIS currents the capture efficiency is > 95%. Also, the full width at half maximum energy spread is 0.5% for high current beams but it is 1.2% for EBIS beams because this design is for high currents. This energy spread could be reduced if necessary by using a debuncher cavity after the RFQ. Thus, using an EBIS with this RFQ, one can obtain ion beams from helium through uranium at 1.0 MeV/nucleon, with virtually all of the ions from the source captured and accelerated for injection into another accelerator or for use in experiments.

Recently, design studies have been initiated for using the RFQ as a buncher for axial injection into a cyclotron. Preliminary results indicate that greater than 90% of the ions from an EBIS with q/A = 0.5 could be bunched into a cyclotron using an RFQ at the cyclotron frequency with an input energy of about 1 keV/nucleon and an output energy of about 10-15 keV/nucleon. Such an RFQ would simply be four insulated vanes driven by an externally resonant rf system. This system would be simple to fabricate and would replace the buncher and electrostatic optics used in present axial injection beam lines with an obvious improvement in the current injected into the cyclotron.[23]

Conclusion

The EBIS as an ion source for use with accelerators has obviously become more realistic with the results reported at this workshop from the new cryogenic versions. Combining the EBIS with the RFQ as the injector for a synchrotron, cyclotron, or linac makes the EBIS even more useful in accelerator applications since this combination results in an ideal match between the ion source and accelerator. Since the RFQ can capture all of the ions from an EBIS and can operate over a wide range of duty factor and frequency, this combination should see use as the injector in all future EBIS high energy accelerator applications.

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